Reactions on ^{40}Ar involving solar neutrinos and neutrinos from core-collapsing supernovae

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We calculated neutrino reactions on ^{40}Ar for detecting core-collapsing supernovae (SNe) neutrinos. The nucleus was originally exploited to identify the solar neutrino emitted from ^{8}B produced in *pp* chains on the Sun. With the higher energy neutrinos emitted from the core-collapsing SNe, contributions from higher multipole transitions, as well as from the Gamow-Teller and Fermi transitions, are shown to be important ingredients for understanding reactions induced by the SN neutrino. Moreover, higher excited states beyond a few states known in experiment diminish significantly the expected large difference between the cross sections of ν_e and $\bar{\nu}_e$ reactions on ^{40}Ar, which difference is anticipated because of the large Q value in the $\bar{\nu}_e$ reaction. The reduction is shown to lead to a difference between them of only a factor of 2.

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Neutrino reactions on ^{40}Ar are of astrophysical importance because the reactions are used to detect the solar neutrino emitted from ^{8}B in the Sun through the liquid argon time projection chamber (LArTPC) in ICARUS (Imaging of Cosmic and Rare Underground Signals) [1]. Since the maximum energy of the solar neutrino is thought to be about 17 MeV in the standard solar model, the neutrino reactions are sensitive to discrete energy states of ^{40}Ar. The Q value for the ^{40}Ar$(\nu_e,e^-)^{40}$K* reaction is 1.50 MeV, while it is 7.48 MeV for the ^{40}Ar$(\bar{\nu}_e,e^+)^{40}$Cl* reaction. Moreover, in ^{40}Cl* only two excited states for the Gamow-Teller (GT) transition are known with no excited isobaric analog states. Therefore, the ^{40}Ar$(\bar{\nu}_e,e^+)^{40}$Cl* reaction might be kinematically disfavored in the solar neutrino. In this respect, ^{40}Ar was claimed to effectively distinguish the ν_e and $\bar{\nu}_e$ emitted from the Sun.

Recently, Ref. [2] revised previous work [3] by focusing on the possible detection of neutrino oscillation of supernova (SN) neutrinos. The SN neutrinos may give valuable information about neutrino properties, such as the ν mixing angle θ_{13} and the mass hierarchy, because they traverse regions of dense matter in the exploding star where matter-enhanced oscillations take place.

One possible way to extract such information is to investigate the abundances of light nuclei, ^{7}Li and ^{11}B, which are abundantly produced through the ν process, that is, ν-induced reactions on related nuclei in core-collapsing SNe [4,5]. Since the ν-induced reaction might be sensitive to the ν properties as well as ν flavors, their abundances could be sensitive to the ν parameters.

Another way is to directly detect the ν signals coming from core-collapsing SN explosions on the Earth through the LArTPC detector [6]. This ICARUS-like detector is also planned to detect the neutrino beam at CERN [7].

Since neutrino energies from SN explosions are expected to be higher than those stemming from the solar neutrino [4,5], one needs to consider the contributions from higher multipole transitions. Random phase approximation (RPA) calculations [2,3,8] showed that contributions from higher multipoles, such as spin dipole resonances (SDR), could be important for the SN neutrino. The importance of higher multipole transitions has recently been confirmed by shell model (SM) calculations [5] and also by quasiparticle random phase approximation (QRPA) calculations [9,10]. The energies and flux of the neutrinos emitted from core-collapsing SN explosions are believed to be peaked from the few to tens of MeV energy region [4,5]. Therefore, the $\nu(\bar{\nu})$-induced reactions on ^{40}Ar are sensitive to the higher excited states of the nucleus beyond nucleon thresholds, which eventually decay to lower energy states with the emission of some particles [8].

Here we report more advanced results based on QRPA calculations for $\nu(\bar{\nu})$-^{40}Ar reactions by solar and SN neutrinos, whose energy ranges are considered up to the 30 and 80 MeV regions, respectively. In particular, we focus on the roles of higher excited states around 20 MeV, although they have not been verified by experiment. Our results decrease the cross sections of the ^{40}Ar$(\nu_e,e^-)^{40}$K* reaction by about 3.5 times and increase by about twice those of the ^{40}Ar$(\bar{\nu}_e,e^+)^{40}$Cl* reaction, compared to previous calculations [2,3]. Consequently, the expected factor of 12 difference between the reactions at $E_\nu = 80$ MeV is drastically reduced to about a factor of 2.

Since our QRPA formalism for neutrino-nucleus reactions is detailed in Refs. [9,10], here we summarize two important characteristics compared to other QRPA approaches. First, the Brueckner G matrix is employed for two-body interactions inside nuclei by solving the Bethe-Salpeter equation based on the Bonn CD potential. This may enable us to reduce some ambiguities from nucleon-nucleon interactions inside nuclei.

Second, we include neutron-proton (*np*) pairing as well as neutron-neutron and proton-proton pairing correlations. In medium or medium-heavy nuclei, *np* pairing affects relevant transitions because of small energy gaps between proton and neutron energy spaces [10]. Moreover, *np* pairing leads to a unified description of both charged current (CC) and neutral current (NC) reactions within a framework shown later on. The results of our QRPA calculations have successfully described

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relevant ν-reaction data for ^{12}C, ^{56}Fe, and ^{56}Ni [9], and ^{138}La and ^{180}Ta [10].

Matrix elements of any weak transition operator $\hat{O}$ between a ground state and an excited state $|\omega; JM\rangle$ are calculated for CC and NC neutrino reactions as follows:

$$\langle \omega; JM||\hat{O}_\lambda||QRPA\rangle_{\rm CC} = \sum_{\alpha\alpha' b\beta'} [\mathcal{N}_{a\alpha' b\beta'} \langle a\alpha'||\hat{O}_\lambda||b\beta'\rangle (u_{pa\alpha'} v_{nb\beta'} X_{a\alpha' b\beta'} + v_{pa\alpha'} u_{nb\beta'} Y_{a\alpha' b\beta'})],$$

$$\langle \omega; JM||\hat{O}_\lambda||QRPA\rangle_{\rm NC} = \sum_{\alpha\alpha' b\beta'} [\mathcal{N}_{a\alpha' b\beta'} \langle a\alpha'||\hat{O}_\lambda||b\beta'\rangle (u_{pa\alpha'} v_{pb\beta'} X_{a\alpha' b\beta'} + v_{pa\alpha'} u_{pb\beta'} Y_{a\alpha' b\beta'}) - (-)^{j_a+j_b+J} \mathcal{N}_{b\beta' a\alpha'} \langle b\beta'||\hat{O}_\lambda||a\alpha'\rangle (u_{pb\beta'} v_{pa\alpha'} X_{a\alpha' b\beta'} + v_{pb\beta'} u_{pa\alpha'} Y_{a\alpha' b\beta'})] + (p \to n), \quad (1)$$

with a normalization factor $\mathcal{N}_{a\alpha' b\beta'}(J)$. The ground state of a target nucleus $|QRPA\rangle$ is described by the BCS vacuum for a quasiparticle that comprises all types of correlations. Excited states $|m; J^\pi M\rangle$ in a compound nucleus are generated by operating the phonon operator on the initial nucleus [9]. Here Roman letters indicate single particle states, and Greek letters with a prime mean quasiparticle type 1 or 2. The amplitudes $X_{a\alpha',b\beta'}$ and $Y_{a\alpha',b\beta'}$, which stand for forward and backward going amplitudes from ground states to excited states, are obtained from the QRPA equation [9,10]. By switching off the *np* pairing, these forms are also easily reduced to the result of the usual pnQRPA.

The weak-current operators $\hat{O}_\lambda$, composed of longitudinal, Coulomb, electric, and magnetic operators, are detailed in Refs. [9,10]. Finally, based on the initial and final nuclear states, cross sections for $\nu(\bar{\nu})$ reactions are calculated by following Ref. [9]. For CC reactions we multiplied the Cabbibo angle $cos^2\theta_c$ and considered the Coulomb distortion of outgoing leptons in a residual nucleus.

In Fig. 1, we show the results for CC reaction ^{40}Ar$(\nu_e,e^-)^{40}$K* up to 80 MeV. For solar neutrinos whose energy range is below 30 MeV, cross sections are fully ascribed to the GT and Fermi transitions. Other transitions contribute only a few percent to the cross section below the 30 MeV region. These results justify previous SM calculations for solar neutrino reactions on ^{40}Ar [11], which consider only the GT and Fermi transitions.

But for SN neutrinos up to 80 MeV, contributions from SDR (1^- and 2^-) are increased to that by the Fermi transition around 55 MeV and become larger by about 2 $\sim$ 2.5 times beyond the region. Other higher multipole transitions ($2^\pm$, $3^\pm$, and $4^\pm$) contribute 10% maximally. Of course, both GT and Fermi transitions are still the main components. The dominance of the GT and Fermi transitions is typical of CC reactions in even-even nuclei, for example, ^{12}C, ^{56}Fe, and ^{56}Ni [9].

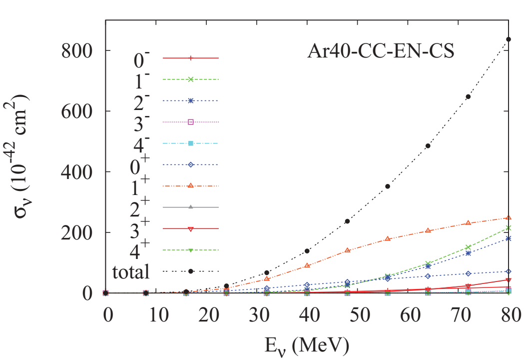

FIG. 1. (Color online) Cross sections by CC reaction ^{40}Ar$(\nu_e,e^-)^{40}$K* for solar and SN neutrinos. For solar (SN) neutrinos, $E_{\nu_e}^{\rm max}$ = 30 (80) MeV is assumed for $J^\pi = 0^\pm \sim 4^\pm$ states.

Our cross sections in Fig. 1 are smaller over the entire energy region by about 3.5 times than those of previous RPA calculations [2] because of the following facts: We include excited states of ^{40}K* up to a few tens of MeV, while the RPA calculation [2,3] seems to take only a few excited states known by experiment.

For instance, in Fig. 2 we show the GT(–) strength distributions and their running sums. The higher the energy states we go to, the larger the strengths and running sums obtained. Specifically, discrete energy states in the 10 $\sim$ 20 MeV region reduce cross sections significantly compared to those calculated by a few known states. If we take the few known states, the cross sections are easily increased and match well the RPA calculation simply because of the increase of the outgoing lepton energy in the kinematics.

Recent calculation of ^{40}Ar(ν,e^-) by the local density approximation [12], which does not explicitly include discrete excited states, also shows such a tendency. Very recently, GT strengths up to 8 MeV were extracted from the ^{40}Ar(p,n) reaction [13]. Based on the strength distribution, ν_e reactions on ^{40}Ar are deduced and shown to be consistent with those by β decay on ^{40}Ti [14]. Neutrino cross sections of ^{40}Ar(ν,e^-) obtained from the GT and Fermi transitions were very similar to the previous results calculated from a few experimental excited states [2] around the few MeV region.

The consistency of our results with the experimental GT(–) strength can be shown by studying the strength distribution and its running sum in the lower energy states in Fig. 2. Our GT strengths are localized at 3.6 (2.1), 3.7 (2.2), 8.6 (7.1), and 8.9 (7.4) MeV from the ^{40}Ar (^{40}K) ground state, which seems to be consistent with the data from the ^{40}Ar(p,n) reaction [13], apart from their strengths. The running sum up to 9 (7.5) MeV, 4 $\sim$5, deduced from the ^{40}Ar(p,n) reaction is also nicely reproduced in our approach by multiplying $(g_V/g_A)^2$ by our result, 3.6. The GT strength derived by our QRPA is thought to be reliable enough to justify our conjecture on the role of higher excited states.

This reduction of cross sections by the higher excited states should function on the ^{40}Ar$(\bar{\nu}_e,e^+)^{40}$Cl* reaction, whose

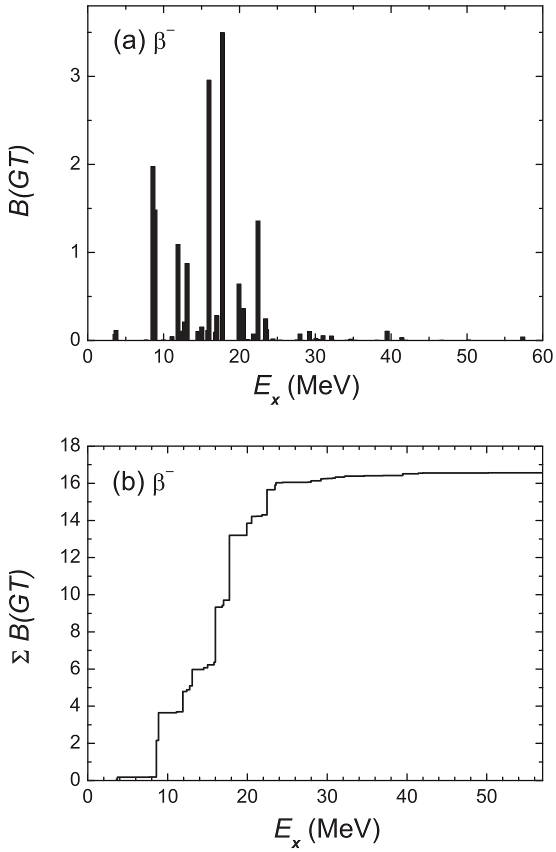

FIG. 2. The GT(−) strengths (a) from ^{40}Ar and their running sum (b) as a function of the excited energy of ^{40}Ar.

results are shown in Fig. 3. The energy dependence of the GT, Fermi, and SDR transitions is very similar to the results of $^{40}Ar(\nu_e,e^-)^{40}K^*$. For solar neutrinos (below 30 MeV), the GT and Fermi transitions are the main components, but the SDR (1^- and 2^-) contributions emerge largely for the SN neutrinos. Cross sections by $\bar{\nu}_e$ for solar neutrinos are almost the same as the those by the ν_e reaction, while they are about half those by the ν_e reaction for SN neutrinos.

This is in contrast to the results of Refs. [2,3]. Actually, these results showed a difference of about a factor of 12 between the ν_e and $\bar{\nu}_e$ reactions in the cross section at $E_\nu = 80$ MeV. Since the Q value for the $\bar{\nu}_e$ reaction, 7.48 MeV, decreases the incident neutrino energy as $E_i^\nu \rightarrow E_i^\nu - Q$, it plays a role in reducing the $\bar{\nu}_e$ cross section for a given energy.

However, the higher excited states weaken the decrease of cross sections by the Q value, so that the expected large decrease of cross sections by the Q value may not be so noticeable. Our cross sections by $\bar{\nu}_e$ are about twice as large as those of Refs. [2,3]. Since the cross sections by ν_e become smaller by about 3.5 times than those in previous calculations, the total difference between the ν_e and $\bar{\nu}_e$ reactions turns out to be only a factor of $2 \sim 3$. Higher excited states are directly associated with the reason why we have only about a factor of 2 difference at $E_\nu = 80$ MeV between the ν_e and $\bar{\nu}_e$ reactions.

In general, the $\bar{\nu}_e$ cross sections up to the few tens MeV region are nearly the same as those by ν_e if we investigate the results for other nuclei. Actually, the difference between $\bar{\nu}_e$-A and ν_e-A reactions is given by the interference term of magnetic and electric transitions. This means that the main interactions for ν-^{40}Ar stem from the longitudinal and Coulomb transitions. Nuclear effects such as the Q value are not so large as to give rise to such a large difference, at least in the SN neutrinos, if we consider the higher excited states.

The Fermi function for the Coulomb correction is used on the energy region below 40 MeV, and the effective momentum approach (EMA) is taken beyond 40 MeV. Coulomb corrections do not affect the difference between the $\bar{\nu}_e$-A and ν_e-A reactions. Both reactions are increased by about 15% maximally by the Coulomb distortion. For pairing interactions, $g_{nn} = 1.105$, $g_{pp} = 1.057$, and $g_{np} = 1.5368$ are used to reproduce the empirical pairing gaps $\Delta_{nn} = 1.768$, $\Delta_{pp} = 1.776$, and $\delta_{np} = 0.684$ MeV for ^{40}Ar, respectively [15].

Figure 4 shows the results for the NC reaction $^{40}Ar(\bar{\nu}_e,\bar{\nu}_e)^{40}Ar^*$ for SN neutrinos. They are dominated by the GT transition for solar neutrinos, which accounts for about half of the cross sections for SN neutrinos. This is typical for NC reactions on even-even nuclei [9,10]. The cross sections presented here are smaller than those used in Refs. [2,3] because of the roles of the higher energy states discussed for the CC reactions. All of the results are summarized in Fig. 5 to illustrate the entire neutrino reactions on ^{40}Ar. The cross

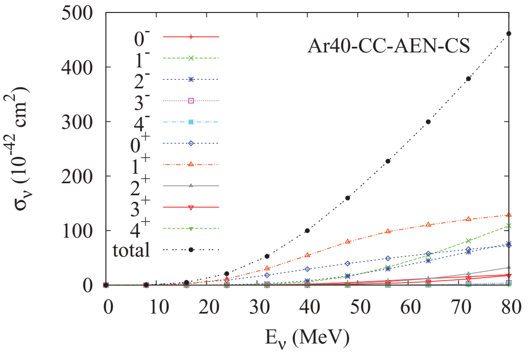

FIG. 3. (Color online) Cross sections by CC reaction $^{40}Ar(\bar{\nu}_e,e^+)^{40}Cl^*$ for SN neutrinos.

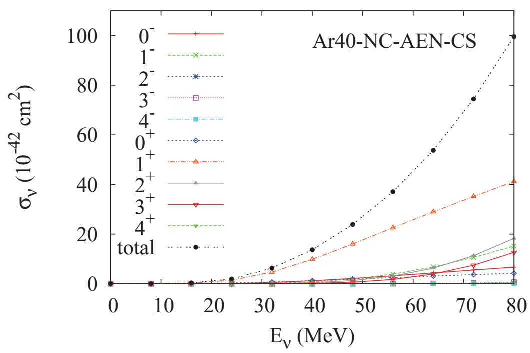

FIG. 4. (Color online) Cross sections by NC reaction $^{40}Ar(\bar{\nu}_e,\bar{\nu}_e^{\prime})^{40}Ar^*$ for SN neutrinos.

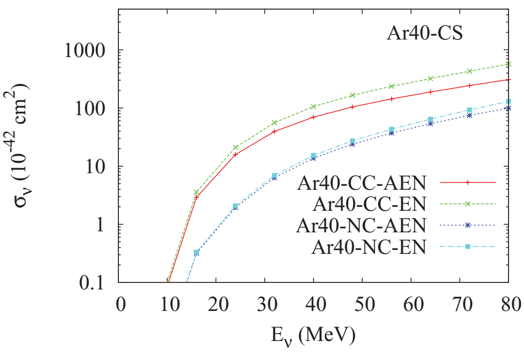

FIG. 5. (Color online) Comparison of cross sections for relevant neutrino reactions on ^{40}Ar given by the log scale for SN neutrinos.

sections by the CC reactions are $4 \sim 5$ times larger than those by the NC reactions.

In summary, we have calculated neutrino-induced reactions on ^{40}Ar by including multipole transitions up to $J^\pi = 4^\pm$ with explicit momentum dependence. Excited states up to a few tens of MeV are taken into account in contrast to previous RPA calculations, which consider only a few states known by experiment. These excited states, specifically those located in the $10 \sim 20$ MeV region, strongly reduce the ν_e cross sections and weaken the decrease of the $\bar{\nu}_e$ cross section owing to the Q value.

With these higher excited states, the large Q value for the ^{40}Ar$(\bar{\nu}_e, e^+)^{40}$Cl* reaction, which motivated discerning the ν_e and $\bar{\nu}_e$ reactions on ^{40}Ar, may not give rise to a difference as drastic as a factor of 12, but lead to a difference of about a factor of 2 between the two reactions. Recent data on the GT strength distributions deduced from the ^{40}Ar(p,n) reaction are shown to be consistent with our results. Therefore, our QRPA results for the $\nu_e(\bar{\nu}_e)$-^{40}Ar reaction could be a useful reference for the detection of SN neutrinos in the LArTPC detector. Of course, more refined calculations such as particle number projected QRPA [16] and deformed QRPA [17] might be helpful for further detailed discussions.

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